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DISPLAY MEASUREMENTS. MEASUREMENT OF REFLECTANCE-TYPE DISPLAYS.(U)

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DISPLAY MEASUREMENTS --- Measurement of Reflectance on Reflective-Type Displays

System Technology Branch
System Avionics Division

February 1979

TECHNICAL REPORT AFAL-TR-79-1029

Final Report for Period 1 January 1977 - 30 September 1978

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report applies the Equation of Spencer and Gray to specify the reflectance of reflective-type displays. This reflectance specification uses both a diffuse component function and a specular component function to completely describe any reflecting surface. The particular display chosen to illustrate the use of this method of specifying reflectance was the Hughes' Liquid Crystal Matrix Display. This display is a matrix display and produces an image by electrically controlling the reflectance of each individual cell. In the appendix, a simplified example using this method of reflectance specification to evaluate a liquid crystal display optical system is given.

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FOREWORD

This report is one of a collection of three technical reports written under Work Unit 20030628, "Liquid Crystal Display Measurements." The topics covered in these reports were chosen to either support this work unit directly or to help provide needed information for Work Unit 20030626, "The Integrated HUD." This work was accomplished during the period of 1 January 1977 to 30 September 1978.

The first report, "Measurement of Reflectance on Reflective-Type Displays," deals with the specification of reflectance in a two component sense. That is, reflectance is specified by both a diffuse component and a specular component. This formulation seems especially useful for specifying the reflectance of liquid crystal displays. However, the method is not limited to displays alone, but applies to any type of reflecting surface. For example, the reflectance of various aircraft coatings could be investigated using this method. The determination of the reflectance of these coatings is important and work has been done in this area, using methods other than the one of this report, by the Air Force Materials Laboratory. It is felt that specifying reflectance by this method may have advantages over other methods in current use. A simplified example using reflectance functions to calculate luminance and contrast ratio of an optical system which uses a liquid crystal display is included in the Appendix of the report.

The second report, "Can MTF Analysis Be Used On Matrix Displays?," investigates the use of modulation transfer function (MTF) in the evaluation of matrix displays. This report concludes that MTF analysis of matrix displays can be useful. An analytical estimate of the MTF of a hypothetical 1000 X 1000 element liquid crystal display is included in the report.

The third and final report of the series is titled "The Effects of HUD Glow On Visual Performance." This report deals with the effects of residual glow in head-up displays, and the effects of this glow on human visual performance. By using the contrast threshold work of Blackwell, it is shown that even small amounts of glow can have detrimental effects on operator performance. The amount of detriment is a function of the level of glow, the operator's state of luminance adaptation, and the perceived contrast ratio between target luminance and surround luminance.

The author thanks all those involved in helping him prepare these reports. I especially want to thank John Coonrod for his support and review of drafts.

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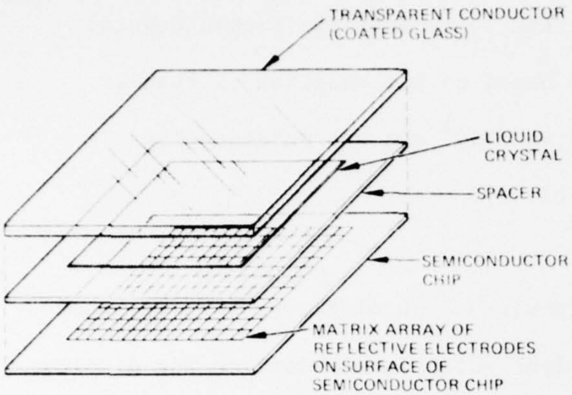
Introduction

A new method of measurement allowing separation of diffuse and specular components of reflectance will prove useful in the evaluation of reflective-type display devices; this report uses the liquid crystal display as an example. The method is based on the equation of Spencer and Gray [1] which was first proposed in 1960[1] and was subsequently validated by laboratory measurements [2, 3].

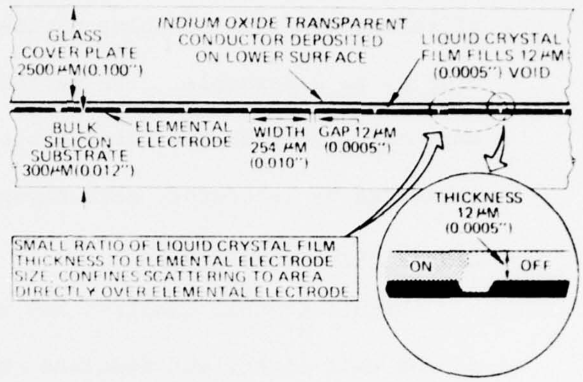
Liquid Crystal Displays

Liquid Crystal Displays are reflective-type displays; that is, they do not emit light, but modulate the light which is incident on the display surface. The display being studied divides the cell surface into a square grid of small cell elements; the reflectance of each element is controlled by external voltages to each cell. (See Figure 1.) One sees that the electrode bus structure forms a grid about each cell on the reflective electrode surface. The grid, in effect, makes the mirror-like surface nonsmooth with a distinctive surface pattern. The liquid crystal material above this surface makes the surface more diffuse, depending on the applied voltage to each cell. Above the liquid crystal material is a cover glass with a thin transparent conductor coating on the underside of the glass. There are several reflection mechanisms occurring in the display device. Some of these mechanisms reflect diffusely; the others specularly. The advantage of considering the device to be a hybrid surface is that each reflection mechanism does not have to be studied separately. This also makes certain that any interaction between reflection mechanisms is accounted for.

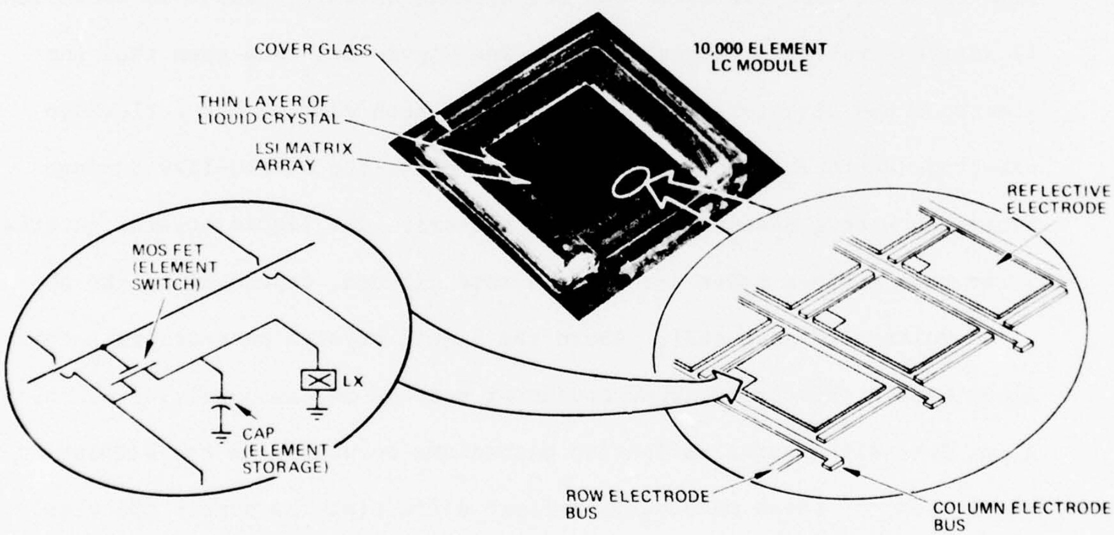
1 The equation was later generalized by Spencer and Gaston; see Ref. 6.



Basic display cell.



Cross section of assembled cell.



Placement of electrical components.

(From Reference 5)

FIGURE 1

DETAILS OF LIQUID CRYSTAL DISPLAY CONSTRUCTION

It is believed that the liquid crystal cell being a hybrid surface (i.e., mirror-like and diffuse), reflects both a specular and a diffuse component of light, with possible specular components at angles other than those where the angle of incidence of the source equals the angle of reflection.

Although overall luminance measurements had previously been made on liquid crystal displays[2], no measurements had been made to quantify the diffuse and specular components of reflectance from the display. Since the very basis of the display operation depends on the strength of these components as a function of viewing angle, source location, and source helios[3] or luminance distribution, these important measurements need to be made.

The Equation of Spencer and Gray

The equation of Spencer and Gray is an integral equation which describes the relationship between the helios $H_{RP}(\ )$ of a point on the surface to the helios $H_{PC}(\ )$ of the source which illuminates the surface. The equation states that $H_{RP}(\ )$ is the sum of two components, a diffuse component and a specular one. The diffuse component is obtained by summing the product of a diffuse reflectance component function ($\rho_d(\ )$) and the incident flux density ($\frac{1}{\pi}H_{PC}(\ )\cos\theta_i\, d\Omega_i$) produced by each infinitesimal region in the hemisphere centered about the point in which there are light sources. The specular component is that which is equal to the product of

---

[2] Measurements have been made both at the Avionics Laboratory and at Hughes Aircraft Company.

[3] Helios (H_{pa}) is defined at a point (p) and in a given direction (a) by $H_{pa} = \pi \frac{D_m}{\omega}$ as $\omega \to 0$. D_m is the maximum flux density (lumens/unit area) and ω the solid angle between the point and the direction of measurement (i.e., the axis of the solid angle is along the direction of measurement with apex at p). As used in this paper, helios is essentially similar to luminance and may be measured in footlamberts. Substitution of the word luminance for helios and the symbol L for H may be made, if desired.

the source helios function ($H_{PC}(\ )$) and a specular reflectance component function ($\rho_s(\ )$). The equation thus covers the perfectly diffuse case, perfectly specular case, and all cases in between these special cases of reflectance.

Assuming wavelength may be neglected, unpolarized incident light, unpolarized reflected light, perfect propagation medium (non-dissipative, non-emittive, transparent, homogeneous, and isotropic) the following equation was proposed [2] (See Fig 2).

$$H_{RP}(P;\theta_i,\Psi_i;\theta_v,\Psi_v) = \frac{1}{\pi}\int_h [\rho_d(P;\theta_i,\Psi_i;\theta_v,\Psi_v) \times H_{PC}(P;\theta_i,\Psi_i)\cos\theta_i \, d\Omega_i] + \rho_s(P;\theta_i,\Psi_i;\theta_v,\Psi_v)\, H_{PC}(P;\theta_i,\Psi_i). \tag{1}$$

Where

- P: a point of measurement on the reflecting surface
- $\rho_d(\ )$: diffuse reflectance component function (dimensionless)
- $\rho_s(\ )$: specular reflectance component function (dimensionless)
- θ_i,Ψ_i: angles of incidence of source
- θ_v,Ψ_v: angles of view of receiver
- Ω_i: solid angle between source and P
- Ω_v: solid angle between receiver and P
- $H_{RP}(\ )$: Helios function at R in the direction of P
- $H_{PC}(\ )$: Helios function at P in the direction of C
- $\int_h$: Integrate over the hemisphere surrounding the point P

If the variables P; θ_v, Ψ_v are fixed the equation reduces to

$$H_{RP}(\theta_i,\Psi_i) = \frac{1}{\pi}\int_h [\rho_d(\theta_i,\Psi_i)\, H_{PC}(\theta_i,\Psi_i) \times (\cos\theta_i)\, d\Omega_i] + \rho_s(\theta_i,\Psi_i)\, H_{PC}(\theta_i,\Psi_i). \tag{2}$$

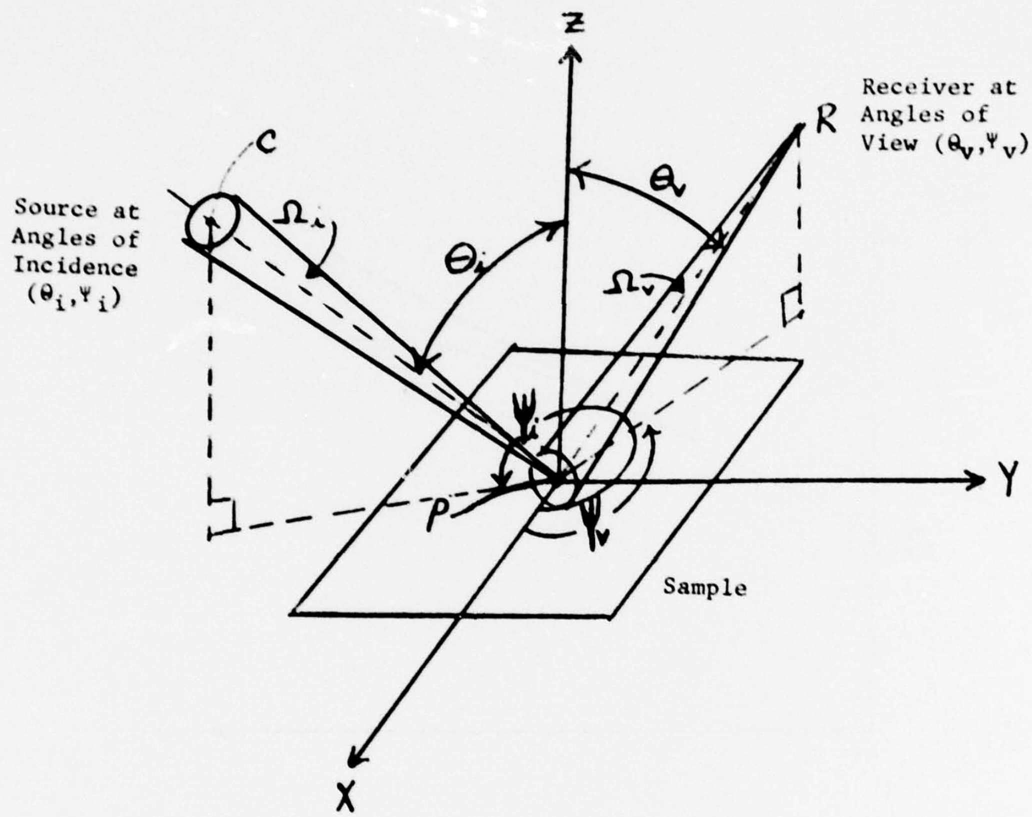
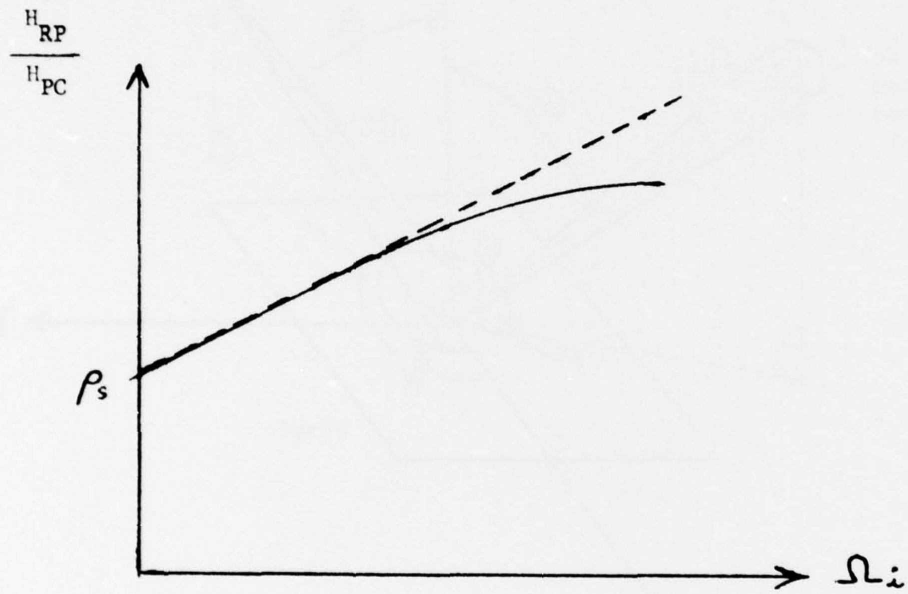


FIGURE 2
(From [3])

GEOMETRY OF MEASUREMENTS



INTERCEPT = ρ_s; SLOPE = $\dfrac{\text{Cos } \theta_i \, \rho_d}{\pi}$

FIGURE 3 (From Reference 2)

PLOT OF EQUATION 3

Restricting the source to a uniform diffuse source of small physical dimensions (which consequently produces a small solid angle), the equation becomes (at each (θ_i,Ψ_i) combination)

$$H_{RP} = \frac{1}{\pi} (\rho_d H_{PC} \cos\theta_i \Omega_i) + \rho_s H_{PC}.$$

Solving for $\frac{H_{RP}}{H_{PC}}$ yields $\frac{H_{RP}}{H_{PC}} = \frac{(\cos\theta_i \rho_d)}{\pi} \Omega_i + \rho_s.$ (3)

It is in this simpler form that the equation may be used in the laboratory. The equation is in the form of $y = mx + b$. As shown in Fig 3, it asymptotically approaches a straight line for small values of Ω_i.

Measurement Techniques

Measurements are taken by placing a photometer in the desired direction of view and recording the ratio of helios of the display surface at the point of measurement to the helios of the source for various small values of incident solid angle Ω_i (as Ω_i becomes smaller). The solid angle is reduced by changing the aperture of the source. Figure 4 illustrates the procedure. This yields data points which when plotted produce curves similar to Fig 3. From these curves the values of ρ_d and ρ_s at a particular (θ_i,Ψ_i) may be determined; ρ_s is the intercept, ρ_d is contained in the slope

$$(\rho_d = \frac{\pi m}{\cos\theta_i}, \ m = \text{slope}).$$

The amount of data needed may be estimated by the following formula: Data points (D.P.) = (receiver locations) x (points on the surface) x (source locations) x (number of solid angles used at each angular measurement).

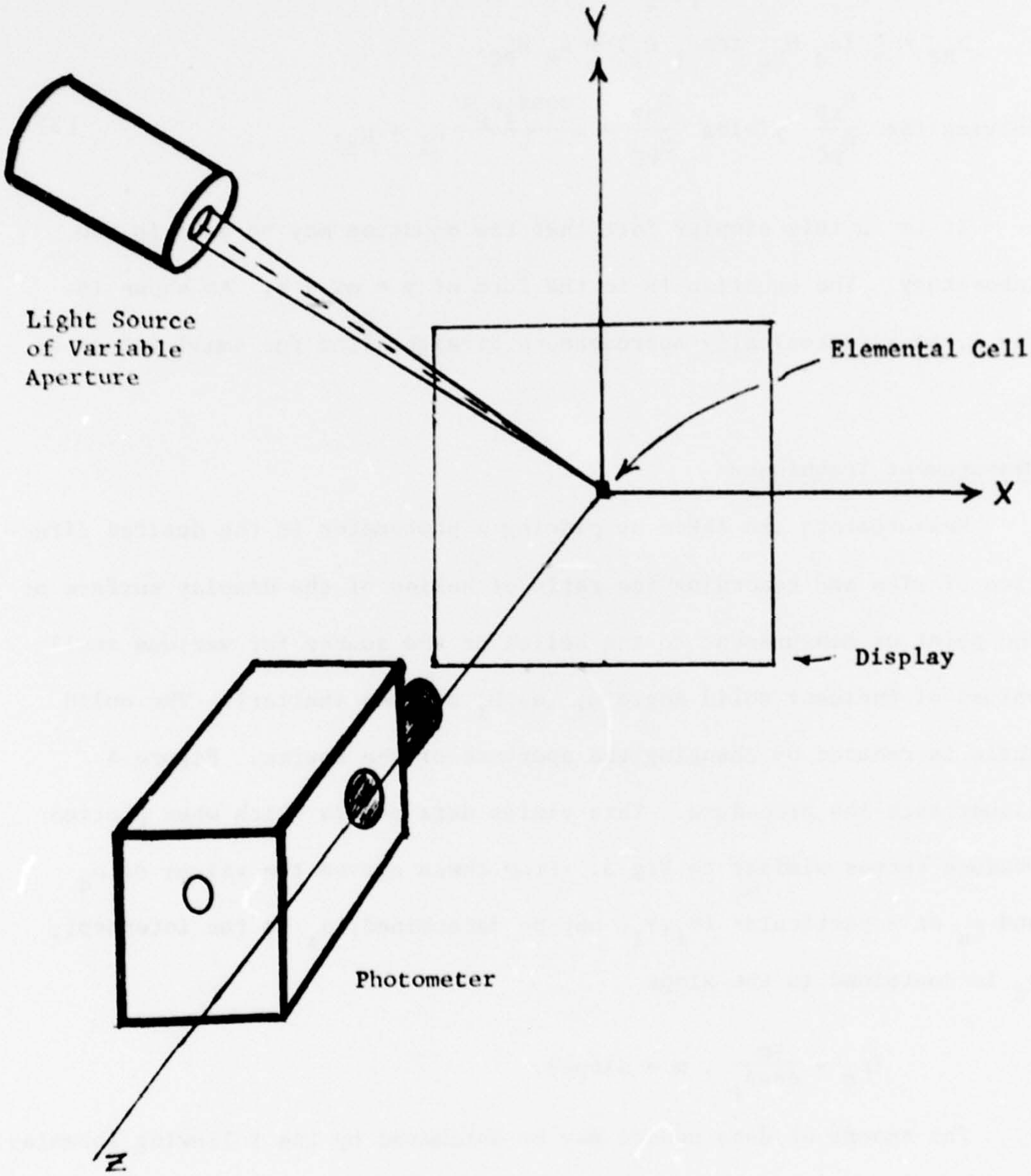


FIGURE 4

MEASUREMENT SET-UP

In the following example, one wishes to find the reflectance functions for a point P. The source may be contained within the angular space, $a \leq \theta_i \leq b$; $c \leq \Psi_i \leq d$ (see Fig 5). The receiver location is fixed. Eight values of Ω_i (incident solid angle) will be used. It is felt that knowing ρ_d and ρ_s at every 3° lattice point will allow reconstruction of the functions. Let $|a-b|$ and $|c-d| = 30°$, then using the formula

$$\text{D.P.} = (1)\ (1)\ \left(\frac{30°}{3°} \cdot \frac{30°}{3°}\right)\ (8)$$

$$\text{D.P.} = 800 \text{ (data points)}.$$

If ρ_d and ρ_s change rapidly in some area the lattice would have to be finer. Values of ρ_d and ρ_s are tabulated. The functions are reconstructed by suitable means (surface curve fitting) to give functions of θ_i and Ψ_i.

Using the ρ_d and ρ_s Functions

Assume we now place a source of known helios distribution $H_{PC}(\theta_i,\Psi_i)$ within the area just measured. The helios function of a real source could be determined by a measurement/surface fitting procedure. Using equation 2 the helios H_{RP} may be determined. (H_{RP} is the helios function value at R in the direction of P due to the extended source.) Equation 2 becomes

$$H_{RP} = \frac{1}{\pi}\int_{h'} \rho_d(\theta_i,\Psi_i)\ H_{PC}(\theta_i,\Psi_i)\ \cos\theta_i\ d\Omega_i$$
$$+ \sum_{j=1}^{M-1}\ \sum_{k=1}^{N-1}\ \rho_s((\theta_i)_j,(\Psi_i)_k)\ H_{PC}((\theta_i)_j,(\Psi_i)_k). \qquad (4)$$

where

$j = (1,3,5,\ \ldots\ M-1)$ M = number of polar subdivisions;

$k = (1,3,5,\ \ldots\ N-1)$ N = number of azimuthal subdivisions.

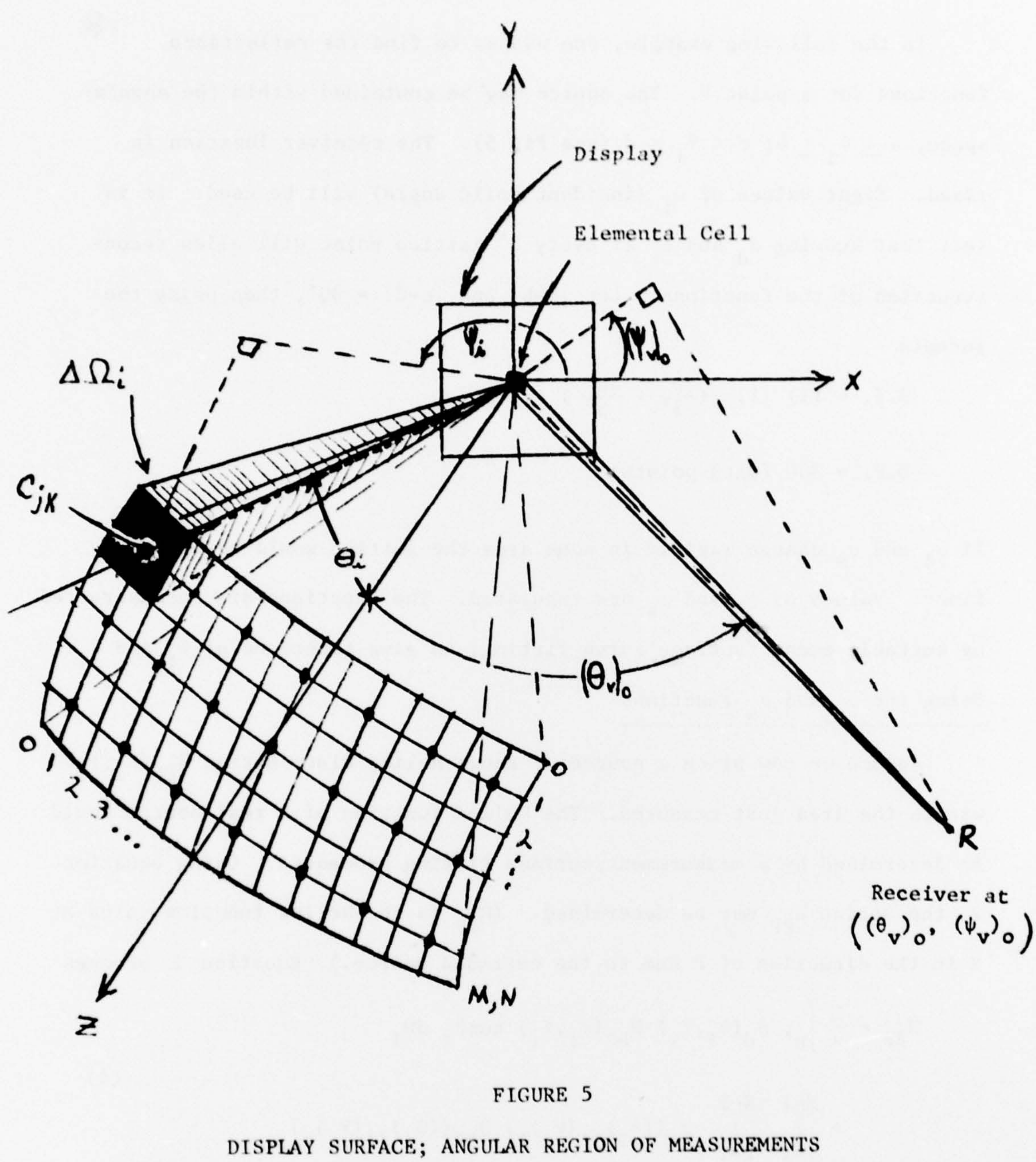


FIGURE 5

DISPLAY SURFACE; ANGULAR REGION OF MEASUREMENTS

In Figure 5, angular region subtended by the lattice is the source region h'. Lattice points represent various $[(\theta_i)_j, (\psi_i)_k]$. Shaded elemental source region C_{jk} subtends solid angle $\Delta\Omega_i$ and represents area in which $H_{PC}(\theta_i, \psi_i) \cdot \rho_s(\theta_i, \psi_i)$ is essentially constant. This allows for specular components for $(\theta_i, \psi_i) \neq [(\theta_v)_o, (\psi_v)_o + \pi]$ if such components exist.

The angular area in Figure 5 has been divided into an even number of curvilinear squares. The grid is aligned such that a $(\theta_i)_j, (\Psi_i)_k$ coordinate equals the $((\theta_v)_o, (\Psi_v)_o + \pi)$ coordinate. The summation of specular components may only need be evaluated at $((\theta_i)_j, (\Psi_i)_k) = ((\theta_v)_o, (\Psi_v)_o + \pi)$ if the contribution to H_{RP} at angles other than these proves to be negligible. The integral above could be approximated by

$$(H_{RP})_{diffuse} = \frac{1}{2\pi} \sum_{j=1}^{M-1} \sum_{k=1}^{N-1} [\rho_d((\theta_i)_j, (\Psi_i)_k)\, H_{PC}((\theta_i)_j, (\Psi_i)_k)$$

$$\times \sin(2 \cdot (\theta_i)_j)\, \Delta\theta\Delta\Psi \ .$$

Preliminary Measurements

To date measurements have been made on a display to verify the Spencer-Gray equation measurements approach. It was found that for small values of Ω_i curves similar to Fig 3 are obtained. This shows that the reflectance from the display can be broken up into components and studied in a more meaningful way.

Future Measurements

Measurements will be made with the intent of viewing a particular point on the display (within a cell) at a fixed viewing angle. The location and size of the source will be limited, reducing the total number

of measurements to be made, yet giving useful information about the display. (See Fig 5). Of course to completely characterize the display reflectance, the measurements will have to be expanded to include all combinations of source and receiver angles of interest for various points P on the surface.

Other Possible Uses of the Measurements

Some other uses of the measurements are:

1. Cell operation definition in terms of two light components. This allows analysis of the cell reflectance when the liquid crystal material is changed slightly. The amount of change may now be noted and compared to reflectances obtained with previous materials.

2. Analysis of direct view displays allowing prediction of brightness and contrast ratio of a cell at a particular viewing angle.

Direct view displays may be analyzed in a general case. That is, once the reflectance functions have been determined, the appearance of the display may be computed for various lighting and/or viewing arrangements.

For example, assume we know the general location of the light source and the normal and worst case viewing conditions (Fig 6). The reflectance functions are found via the Spencer-Gray equation approach for the required source angular region and receiver angles of view. With this data the appearance of the cell with any other source of known helios distribution within the area of measurements (and therefore known reflectance functions) may be computed. For real sources, the helios distribution would be determined by measurement. Mathematical models of hypothetical sources could also be used. This would allow determination of the best source for a particular geometric restriction on the location of the source.

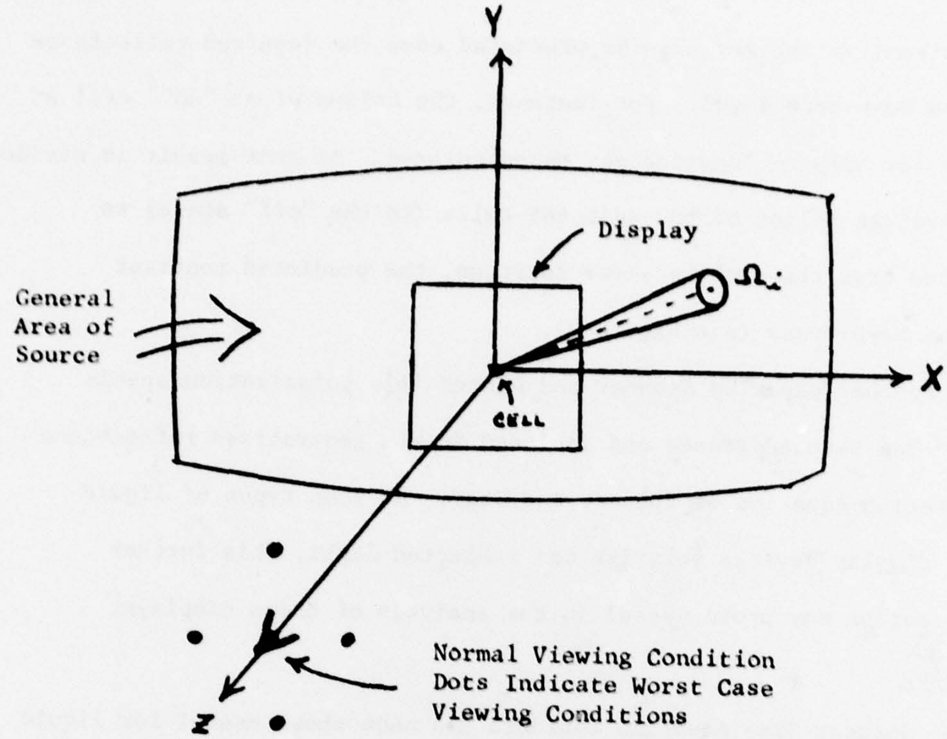
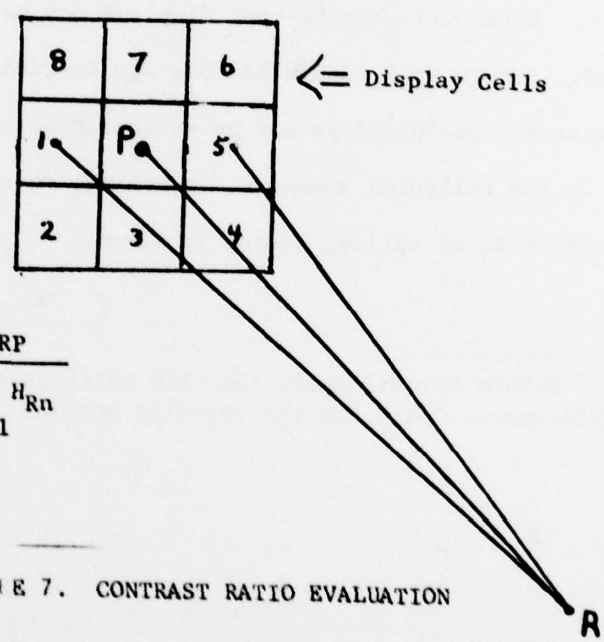


FIGURE 6. ANALYZING A DIRECT-VIEW DISPLAY



$$CR = \frac{H_{RP}}{\frac{1}{8}\sum_{n=1}^{8} H_{Rn}}$$

FIGURE 7. CONTRAST RATIO EVALUATION

Contrast ratios may also be predicted once the required reflectance functions have been found. For instance, the helios of an "on"[4] cell at a particular viewing location may be calculated. If this result is divided by the average helios of the adjacent cells (in the "off" state) as calculated from the same receiver location, the predicted contrast ratio has been found (see Figure 7).

In another paper by Spencer and Gaston [6], polarization specification has been addressed and included in the generalized reflectance specification equation of Spencer and Gray. As some types of liquid crystal display devices polarize the reflected light, this further generalization may prove useful in the analysis of these displays.

Conclusion

The Spencer-Gray equation approach has been shown useful for liquid crystal display measurements. The equation has been presented and possible uses of the measurement techniques allowed by this equation described. Other reflectance-type displays may be evaluated by this method. Future work should be done and sufficient data taken so that reflectance-type displays may be evaluated in a more precise manner.

In the following appendix, an example using this technique in the evaluation of an optical system is given.

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[4] "On" refers to cell operation with voltages that maximize the diffuse reflectance; "off" has the opposite meaning.

APPENDIX

CALCULATING THE IMAGE LUMINANCE OF AN OPTICAL SYSTEM USING REFLECTANCE FUNCTIONS

In this example, the luminance of the image of the optical system[1] shown in Figure 8 will be calculated for a point on the optical axis. Also, the contrast ratio of a bright-to-dark cell will be found. The system is comprised of a liquid crystal display, an ellipsoidal reflector, an arc lamp with associated spherical reflector, a lens, and a screen. The calculation will be described as a sequence of steps below.

1. Calculate Arc/Spherical Mirror Luminance.

Assume the arc is spherical in shape with a 0.1" diameter. Assume its luminance is uniformly diffuse, and that the spherical reflector behind the arc restricts the emitted power to the front 2π steradians. The luminance of the arc/mirror combination is given by

$$H = \frac{\pi I}{S} \tag{6}$$

where

$$I = \frac{(1 + \rho)F}{4\pi} \tag{7}$$

H is the luminance in footlamberts; I is the intensity in candelas; F is the flux output in lumens; and ρ is the specular reflectance of the spherical mirror. S is the projected circular area of the arc in ft^2.

1 - Patent Pending; Hughes Aircraft Company

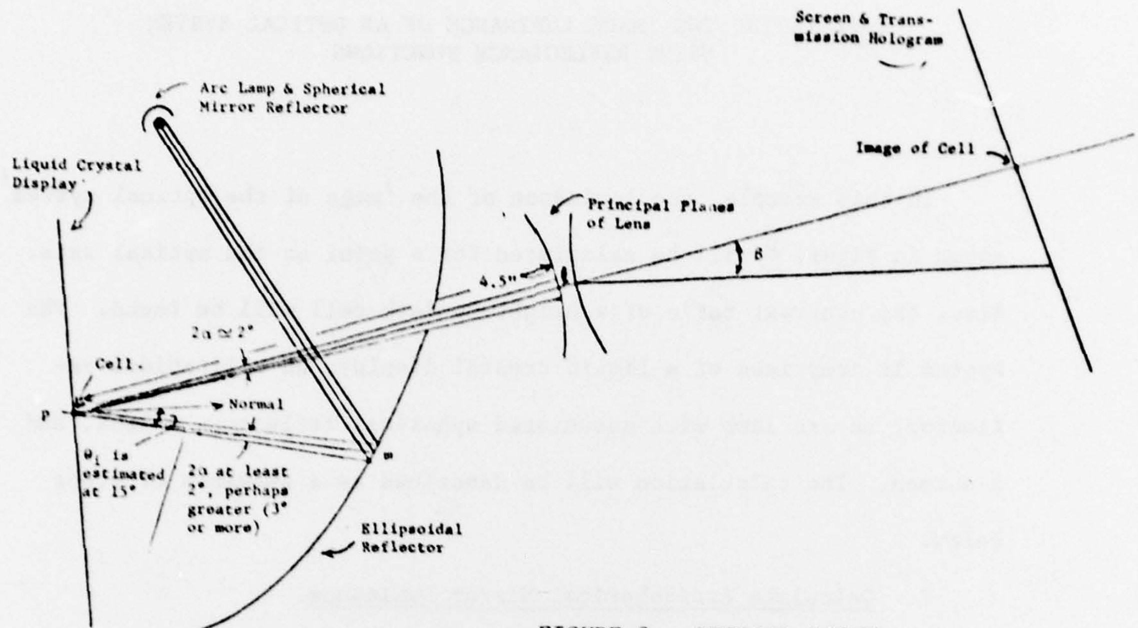

FIGURE 8. OPTICAL SYSTEM

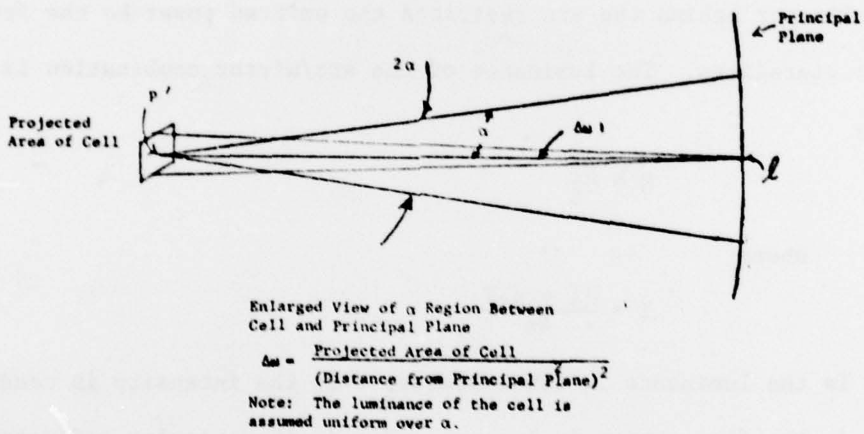

FIGURE 9. ENLARGED VIEW OF FIGURE 8

Since F is given as 1.25 watts at 0.91 luminosity,

$$F = 1.25 \text{ watts} \times 0.91 \times 680 \text{ lumens/watt} = 773.5 \text{ lumens.}$$

From equation 7,

$$I = (1 + 0.9)\ (773.5)/4\pi = 117 \text{ candelas.}$$

Substituting into equation 6 gives

$$H = \pi(117)\ /\ (0.05/12)^2\pi = 6739200 \text{ footlamberts.}$$

Since the arc/mirror combination is covered with UV and IR filters, H must be multiplied by τ, the transmission coefficient of the filters, to give

$$H = 0.86\ (6739200) = 5795712 \text{ footlamberts.}$$

The luminance seen by the liquid crystal cell (p) in the direction of a point (m) on the ellipsoidal mirror is equal to the specular reflectance of the mirror times H, giving

$$H_{pm} = 0.9H = 5216141 \text{ footlamberts.}$$

2. Calculate the Liquid Crystal Cell Luminance.

Assuming that the diffuse component of the cell reflectance is negligible compared to the specular component when the cell is bright,

$$H_{1p} = \rho_s\ H_{pm} \tag{8}$$

This is the luminance of the cell as seen from the principal plane of the lens. ρ_s is given as 0.5 (the specular reflectance of the bright cell).

From equation 8,

$$H_{1p} = 0.5\ (5216141) = 2608071 \text{ footlamberts.}$$

3. Calculate the Illumination at the Principal Plane.

Since the solid angle subtended by the cell to the principal plane is small, the illumination at the principal plane is given by

$$D_1 = 1/\pi \; H_{1p} \; \Delta\omega \tag{9}$$

where

$$\Delta\omega = \frac{\text{Projected area of the cell}}{(\text{distance to the principal plane})^2} \tag{10}$$

Using equation 10,

$$\Delta\omega = (0.01)^2/4.5^2 = 4.94\ (10^{-6})\ \text{steradians}^5.$$

Substituting into equation 9 gives

$$D_1 = 1/\pi\ (2608071)\ (4.94)\ (10^{-6}) = 4.10\ \text{footcandles}\ (\text{lumen/ft}^2)$$

4. Calculate the Flux Input to the Lens.

The flux input to the lens is given by

$$F_1 = D_1 A \tag{11}$$

where A has been assumed to be a spherical surface and is given by

$$A = 2\pi\ r^2\ (1 - \cos\alpha) \tag{12}$$

Substituting the appropriate values from Figure 1 into (12) gives

$$A = 2\pi\left(\frac{4.5}{12}\right)^2 (1 - \cos 1^\circ) = 1.35\ (10^{-4})\ \text{ft}^2$$

Thus from equation 11,

$$F_1 = (4.10)\ (1.35)\ 10^{-4} = 5.54\ (10^{-4})\ \text{lumens.}$$

5. Calculate the Average Illumination at the Screen.

The average illumination of the cell at the screen is given by

$$D_s = \rho_m\ \tau_s\ F/A_s \tag{13}$$

ρ_m is the reflectance of the folding mirrors (not shown in Figure 8)

---

5 This value is approximately 3.5% high due to the neglected cos 15° term required to obtain the projected area.

and is equal to $(0.95)^2$. τ_s is the transmittance of the lens and equals 0.99^2. A_s is the area of the image and is given by

$$A_s = (\text{cell dimension X magnification ratio})^2 \tag{14}$$

Therefore, using equations 13 and 14,

$$D_s = \frac{(0.99)^2\ (0.95)^2\ 5.54\ (10^{-4})}{[(0.01/12)\ (3.2/3.5)]^2}$$

$$= 844 \text{ footcandles}$$

The luminance at the screen is given by

$$H_s = \tau_h \text{ X } G \text{ X } D_s \tag{15}$$

where τ_h is the transmission hologram efficiency, G is the screen gain, and D_s is the average illumination of the cell image. Substituting into equation 15,

$$H_s = 0.8\ (5 \text{ footlamberts/footcandle})\ (844)$$

$$= 3376 \text{ footlamberts.}$$

Normally, off-axis image points luminance are reduced by $\cos^4\beta$. That is, the luminance of the off-axis points is approximately equal to the luminance of the on-axis point multiplied by $\cos^4\beta$. β is shown in Fig. 8. But, in this system the variation has been shown to be greater than the expected.

6. Calculate the Dark Cell Luminance and Contrast Ratio.

When the cell is dark, it is cperating in the "diffuse" mode. Both a diffuse and specular component of reflectance exists. The luminance of the cell may be calculated by

$$H_{1p} = \rho_s H_{pm} + 1/\pi \int \rho_d\ (\theta_i,\Psi_i) \cos\theta_i\ H_{pm}\ (\theta_i,\Psi_i)\ d\omega \tag{16}$$

As an approximation, if H_{pm} is constant and subtends a small solid angle, as seen from the cell,

$$H_{1p} = \rho_s H_{pm} + 1/\pi \sum_{j=1}^{N} (\rho_d)_j \cos\theta_i\ H_{pm}\ \Delta\omega_j \tag{17}$$

The ρ_d function is shown in Figure 9 for two ρ_d functions, plotted as a function of the half angle α. Note that the function has been approximated as a sum of step functions, which allows application of equation 17. From the half angle α, the solid angle subtended by the source may be calculated from

$$\Delta\omega = 2\pi\ (1-\cos\alpha) \tag{18}$$

The ρ_s value is given as 0.01. θ_i has been assumed to be 15^o (Figure 8).

Using (17) and (18) and the first ρ_d function,

$$\begin{aligned} H_{1p} &= 0.01\ (5216141) \\ &+ 1/\pi\ (22)\ (\cos 15^o)\ (2\pi)\ (1-\cos 1^o)\ (5216141) \\ &+ 1/\pi\ (8)\ (\cos 15^o)\ (2\pi)\ (1-\cos 1.5^o)\ (5216141) \\ &= 52161 \text{ (specular component)} \\ &\left.\begin{aligned} &+ 33764 \\ &+ 27625 \end{aligned}\right\} \text{ 61389 (diffuse component)} \\ &= 113550 \text{ footlamberts.} \end{aligned}$$

Although the screen luminance can be calculated, this is not necessary to calculate contrast ratio. Contrast ratio is given by

$$CR = \frac{H_{1p}\text{ (bright)}}{H_{1p}\text{ (dark)}} \tag{19}$$

Substituting into (19),

$$CR = \frac{2608071}{113550} = 23$$

Using the second ρ_d function, where ρ_d is a rectangle function extending from 0 to 1^o, the diffuse component is calculated as

H_{1p} (diffuse) =

$1/\pi$ (30) ($\cos 15^{o}$) (2π) ($1-\cos 1^{o}$) (5216141) = 46042 footlamberts. Adding the diffuse and specular components gives

H_{1p} = 46042 + 52161 = 98203 footlamberts; from (19),

$$CR = \frac{2608071}{98203} = 27.$$

DISCUSSION.

In this example, the values of the various parameters and variables have either been taken from data given by Hughes Aircraft Company or estimated. Thus, the final values of luminance and contrast ratio are only approximate.

The ρ_d and ρ_s functional values should be determined by measurement. The ρ_d function probably exists when the cell is bright, but it would be limited to a small source acceptance angle, giving a small contribution to the bright cell luminance. (Source acceptance angle is discussed below.) The source acceptance angle of ρ_d may be quite large when the cell is dark. Since the dark cell luminance is critical to contrast ratio, this source acceptance angle should be investigated.

Intereflections within the system have been ignored, which, if present, will increase the diffuse component of the cell luminance and decrease the contrast ratio of the bright to dark cell.

The value obtained for cell luminance is highly dependent on the true value of the luminance of the arc lamp/spherical mirror combination, as seen from p through the ellipsoidal mirror. It is suggested that the luminance as seen from the display cell be

established as accurately as possible. This may involve a ray-trace from the cell (p in Figure 8) to the ellipsoidal mirror, to the arc/mirror combination. This will establish the exact value of α, and if the luminance of the arc is known, the luminance function H_{pm} as seen from the display cell.

As noted earlier, the diffuse reflectance function has a source acceptance angle associated with it. That is, the values of ρ_d are, for some surfaces, only significant over a limited range of half angle α (this is the angle between p and m in Figure 8). In reference 9, it is explained how ρ_d may be found as a function of α for axially symmetric reflecting surfaces, which the liquid crystal cell closely approximates. The method illustrated in this reference will aid in the determination of the ρ_d function and consequently the diffuse component of the cell luminance.

It is felt that this method may be made as accurate as needed to determine the image luminance and the bright cell to dark cell contrast ratio. Further, it has the advantage of showing by calculations based on measured values of ρ_d and ρ_s where improvements in the system could be made to increase image luminance and bright to dark cell contrast ratio.

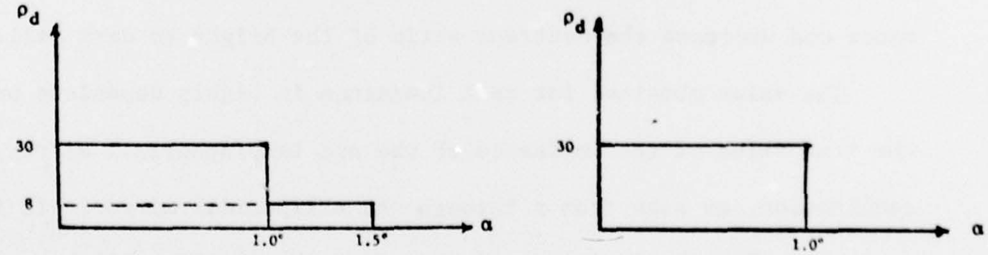

FIGURE 10. ESTIMATED ρ_d AS A FUNCTION OF α (α is the half angle of the source as seen from p)

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NOTE:

Reference 1 - First proposal of theory.

Reference 2 - Compares 8 current definitions of reflectance.

Reference 3 - Gives expected numerical ranges of ρ_d and ρ_s (0 to ∞) possible.

Reference 4 - Discusses concept of helios (luminance).

Reference 5 - Liquid crystal displays and their application to head-up displays discussed.

Reference 6 - Polarization specification discussed and related to reflectance theory.

Reference 7 - Final technical report covering the design and development of a solid state liquid crystal television display.

Reference 8 - This report's treatment of reflectance is similar to the Spencer-Gray approach.

Reference 9 - This reference shows how ρ_d may be found as a function of the half angle subtended by the source. The method is valid for axially symmetric reflecting surfaces.